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V. FLARE STARS AT RADIO WAVELENGTHS

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## FLARE STARS AT RADIO WAVELENGTHS

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**ABSTRACT.** The radio emission from dMe flare stars is discussed using Very Large Array and Arecibo observations as examples. Active flare stars emit weak, unpolarized, quiescent radio radiation that may be always present. Although thermal bremsstrahlung and/or thermal gyroresonance radiation account for the slowly-varying, quiescent radio radiation of solar active regions, these processes cannot account for the long-wavelength quiescent radiation observed from nearby dMe flare stars. It has been attributed to nonthermal gyrosynchrotron radiation, but some as yet unexplained mechanism must be continually producing the energetic electrons. Long-duration (hours), narrow-band ( $\Delta\nu/\nu < 0.1$ ) radiation is also emitted from some nearby dMe stars at 20 cm wavelength. Such radiation may be attributed to coherent plasma radiation or to coherent electron-cyclotron masers. Impulsive stellar flares exhibit rapid variations ( $< 100$  msec) that require radio sources that are smaller than the star in size, and high brightness temperatures  $T_B > 10^{15}$  K that are also explained by coherent radiation processes. Quasi-periodic temporal fluctuations suggest pulsations during some radio flares. Evidence for frequency structure and positive or negative frequency drifts during radio flares from dMe stars is also presented.

### 1. INTRODUCTION

Pioneering single-dish observations in the 1970s showed that dwarf M flare stars occasionally emit radio bursts with extremely high flux densities and brightness temperatures of  $T_B > 10^{12}$  to  $10^{15}$  K if the radio source is comparable to the star in size (see Lang and Willson (1986b) and Kundu and Shevgaonkar (1988) for some historical details). Such powerful radio flares are extremely rare, sporadic and brief, however, leading many to suspect that they might be confused with terrestrial interference. Moreover, identification by correlation with optical flares could not be relied on, for different radiation mechanisms often dominate in the two spectral domains.

Interferometric observations with the Very Large Array (VLA) have unambiguously differentiated stellar radio emission from terrestrial interference, and the large collecting area of both the VLA and the Arecibo Observatory have enabled detection of the relatively weak radio flares that are presumably more frequent than the more powerful ones. One survey, for example, indicates that flaring emission can be detected for about 40% of flare stars nearer than 10 parsecs and visible with the VLA (White, Kundu and Jackson, 1990). Under the assumption that the radio source size is equal to the stellar radius, brightness temperatures of  $T_B = 10^8$  to  $10^{10}$  K and  $T_B = 10^9$  to  $10^{11}$  K have been inferred for the detected stars at 6 cm and 20 cm wavelength, respectively.

Although the observed radio luminosity from stellar flares is only about one thousandth the luminosity observed at X-ray or optical wavelengths, the radio emission is still thousands of times more powerful than solar radio flares, and it serves as an important diagnostic tool for studies of stellar coronae. Such studies have been carried out in detail for the most active dwarf M flare stars listed in Table 1. They are all nearby dMe stars that show evidence for chromospheric activity in the form of Ca II, Mg II and H $\alpha$  emission lines.

Table 1. Accurate 6 cm positions, spectral type, Sp, quiescent flux density,  $S_{Q6}$ , at 6 centimeters wavelength, peak flaring flux density,  $S_{F20}$ , at 20 centimeters wavelength, distance, D, in parsecs, and the logarithm of the quiescent X-ray luminosity,  $\log L_x$ , for radio-active flare stars.

Star	R.A.(1950.0) h m s	Dec.(1950.0) ° ' "	Sp	$S_{Q6}$ (mJy)	$S_{F20}$ (mJy)	D (pc)	$\log L_x$ (erg s $^{-1}$ )
L 726-8A**	01 36 33.314	- 18 12 23.20	dM5.5e	1.0	20	2.7	27.5
UV Ceti**	01 36 33.404	- 18 12 21.56	dM6e	3.2	100	2.7	27.5
YY Gem	07 31 25.691	+31 58 47.23	dM1e	0.4	1	14.5	29.5
YZ CMi	07 42 02.962	+03 40 30.39	dM4.5e	0.5	20	6.0	28.5
AD Leo	10 16 52.604	+20 07 17.59	dM3.5e	1.1	100	4.9	29.0
Wolf 630A,B	16 52 46.455	- 08 15 13.715	dM4.5e	0.9	3	6.2	
AT Mic†	20 38 44.4	- 32 36 49.5	dM4.5e	3.6	6	8.8	29.3
AU Mic	20 42 04.558	- 31 31 17.50	dM0e	0.8	26	8.8	29.8
EQ Peg A††	23 29 20.910	+19 39 41.11	dM5e	0.3	25	6.4	

\*Adapted from Kundu et al. (1987), and Jackson, Kundu and White (1989) for the 6 cm data, with positions accurate to 0".1 or better.

\*\*The separation and position angle of L 726-8A and L 726-8B (UV Ceti) is  $2''.080 \pm 0''.080$  at  $38^\circ.0 \pm 1^\circ.9$ .

†Southern component of a fully resolved binary whose components are both active radio emitters; the northern component lies about 3".6 away at a position angle of about  $15^\circ$ .

††Quiescent emission from both component of EQ Peg A, B has been previously detected with respective 6 cm fluxes of 0.7 and 0.4 mJy and an angular separation of about 3".0 (see Gary (1985)).

This review will focus on these radio-active dMe stars. They include the very few cases in which we can detect the relatively weak (a few mJy), quiescent radio flux of the star (see Section 2). Long-duration, narrow-band radio flares (Section 3) have also been observed from several of these stars; they are unlike anything observed on the Sun.

Powerful (up to 200 mJy), impulsive (a few minutes) radio flares are also emitted by these stars. Such flares exhibit rapid variations (Section 4.1), quasi-periodic fluctuations (Section 4.2), both narrow-band and broad-band features (Section 5) and positive and negative frequency drifts (Section 5).

Figures 1 and 2 illustrate such flares for the dMe star EQ Pegasi. They are often up to 100% circularly polarized. Successive oppositely polarized flares have been detected for EQ Pegasi (Fig. 2) and AD Leonis (Willson, Lang and Foster (1988)), suggesting the presence of both magnetic polarities; but YZ Canis Minoris always exhibits left-handed circular polarization that remains the same over a wide range of wavelength (6 cm to 90 cm), suggesting a global, dipolar magnetic field that is viewed pole-on (Kundu and Shevgaonkar (1988)).

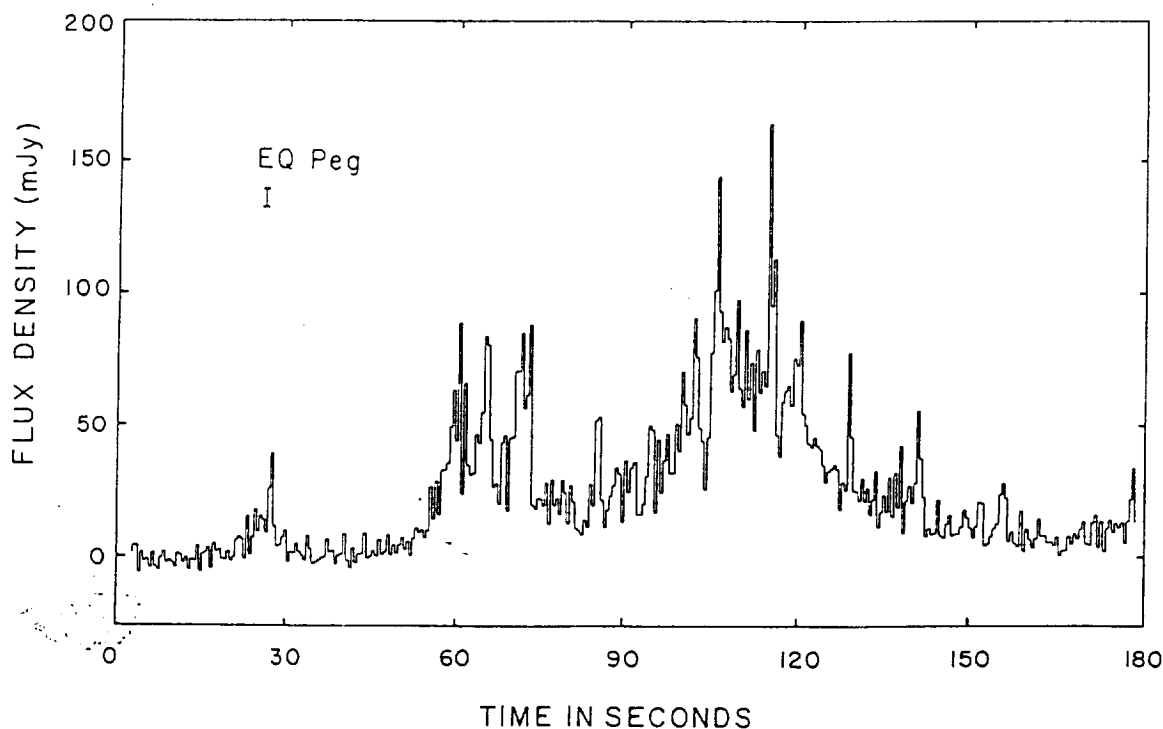


Figure 1. A previously unpublished VLA observation of the total intensity,  $I$ , at 1420 MHz (21 cm) from the dwarf M star EQ Pegasi. The flaring emission has a total duration of minutes, with components on shorter time scales of seconds or less. The radiation is up to 100 percent circularly polarized (see Fig. 2).

## 2. QUIESCENT RADIO EMISSION FROM dMe FLARE STARS

Unpolarized radio radiation that is nearly always present, and shows only slow variations with time, has been termed quiescent radio emission to distinguish it from the highly variable, brief radio flares that are often highly circularly polarized. The quiescent emission has flux densities of a few mJy at 6 cm wavelength (see Table 1 and Gary (1985)). It was at first attributed to thermal radiation from the same electron population that gives rise to the stellar X-ray emission (also see Table 1). If this were the case, it would be consistent with the Sun's slowly varying radiation at centimeter wavelengths; the solar radiation is due to either thermal bremsstrahlung or the thermal gyroresonance radiation of hot ( $10^6$  K) electrons trapped within coronal loops that radiate strongly at X-ray wavelengths.

Nevertheless, thermal emission from the stellar coronae observed in X-rays cannot easily account for the quiescent radiation. Thermal bremsstrahlung of the X-ray plasma is so optically thin at 6 cm wavelength that its flux density is one or two orders of magnitude below the detection limit of the VLA - even when the X-ray plasma covers the entire surface of the nearest flare star.

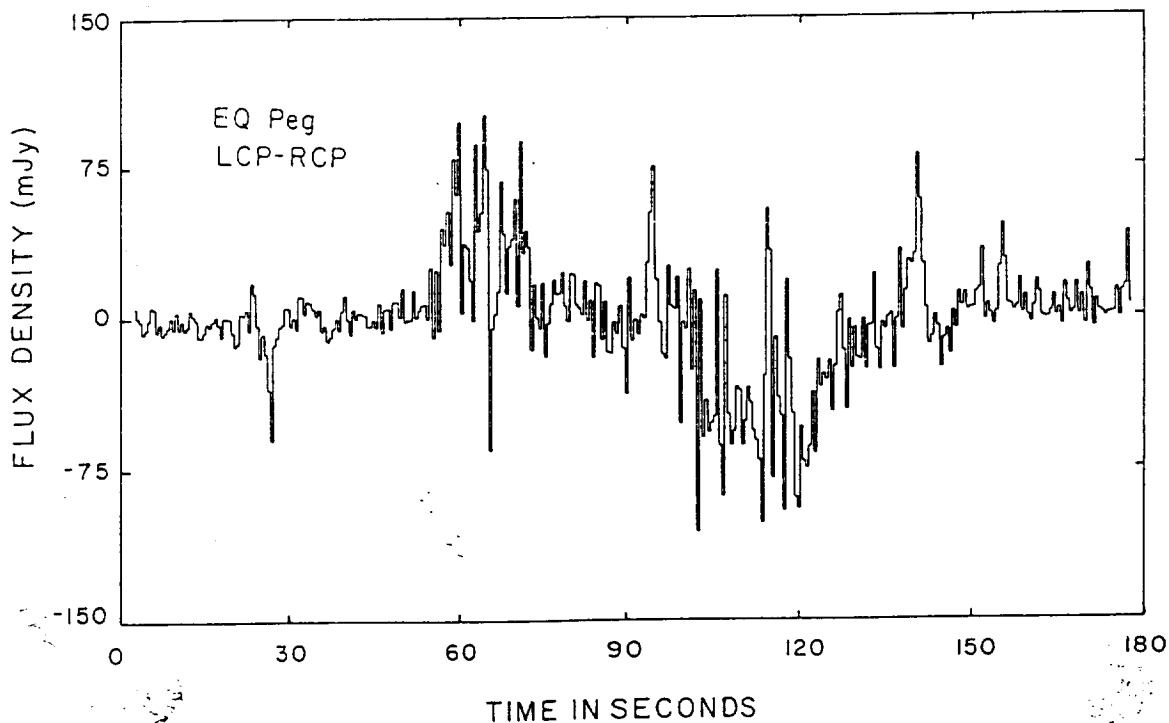


Figure 2. The difference between the left-hand circularly polarized (LCP) and right-hand circularly polarized (RCP) radiation from the dwarf M star EQ Pegasi at 1420 MHz (21 cm). Up to 100 percent circularly polarized radiation is emitted with opposite senses, or directions, for successive bursts (courtesy of Robert F. Willson).

The optical depth can be enhanced for the gyroresonance of thermal electrons in relatively strong magnetic fields. Short-wavelength ( $< 6$  cm) quiescent emission might then be explained by optically thick gyroresonant radiation of the high-temperature tail of the X-ray emitting plasma (Gudel and Benz, 1989). In this case, the radio data require electrons that are at a higher temperature than the average X-ray emitting electrons, and they are probably emitted from a source that is much larger than the star. The maximum observed flux density,  $S$ , is given by the Rayleigh-Jeans law, and the radius of the emitting source is therefore given by:

$$R^2 = 10^{13} \frac{SD^2}{\nu^2 T} \text{ cm}^2,$$

where  $S$  is the source flux density in Jy,  $D$  is the distance in cm,  $T$  is the temperature in K, and the observing frequency is  $\nu = 2.8 \times 10^6 nH$  Hz for the  $n$ th harmonic in a magnetic field of strength  $H$ . Radii comparable to those of the dwarf M stars are only obtained for low flux densities,  $S = \frac{1}{2}$  mJy, short wavelengths,  $\lambda < 6$  cm, high temperatures  $T > 10^7$  K, and nearby dMe flare stars,  $D < 10$  pc.

Thermal gyroresonance radiation cannot explain the long-wavelength,  $\lambda > 20$  cm, quiescent radiation where higher flux densities of  $S = 2$  to 20 mJy have been observed (Lang and Willson, 1986 a, Bastian and Brokbinder, 1987, Gudel and Benz, 1989). The radio source would have to be tens to hundreds of times larger than the star with implausibly intense magnetic fields at these remote locations. This long-wavelength radio emission has been attributed to nonthermal gyrosynchrotron radiation.

The gyrosynchrotron hypothesis requires a hotter corona with smaller sizes and lower densities than the gyroresonance model, but there must be a currently - unexplained, steady source of energetic electrons. Both models have been discussed by Kundu et al. (1987); because the gravitational scale height is comparable to the height of the stellar coronae, magnetic structures are required to confine the radio-emitting plasma. The coronae of nearby dMe flare stars therefore bear a closer resemblance to the Earth's magnetosphere than to the Sun's corona. We do not know if the relevant magnetic structures on the flare stars are due to several small active regions or to a global dipolar field, and we do not know how the radio-emitting electrons interact with the X-ray emitting plasma. The long-wavelength quiescent radiation might alternatively be due to continued, low-level, narrow-band, coherent radiation that resembles radio flares from these stars.

### 3. LONG-DURATION, NARROW-BAND EMISSION

Relatively intense ( $S = 100$  mJy), narrow-band ( $\Delta\nu/\nu < 0.1$ ) radiation lasting for several hours has been observed at 20 cm wavelength in several flare stars (Lang and Willson, 1986; White, Kundu and Jackson, 1986; Kundu et al., 1987; Lang and Willson, 1988). These

long-duration events are slowly variable, so they might be more energetic version of the process that accounts for the quiescent radiation. However, the long-duration, narrow-band radiation is highly circularly polarized, so its polarization bears a closer resemblance to the stellar flares than to the unpolarized quiescent radiation.

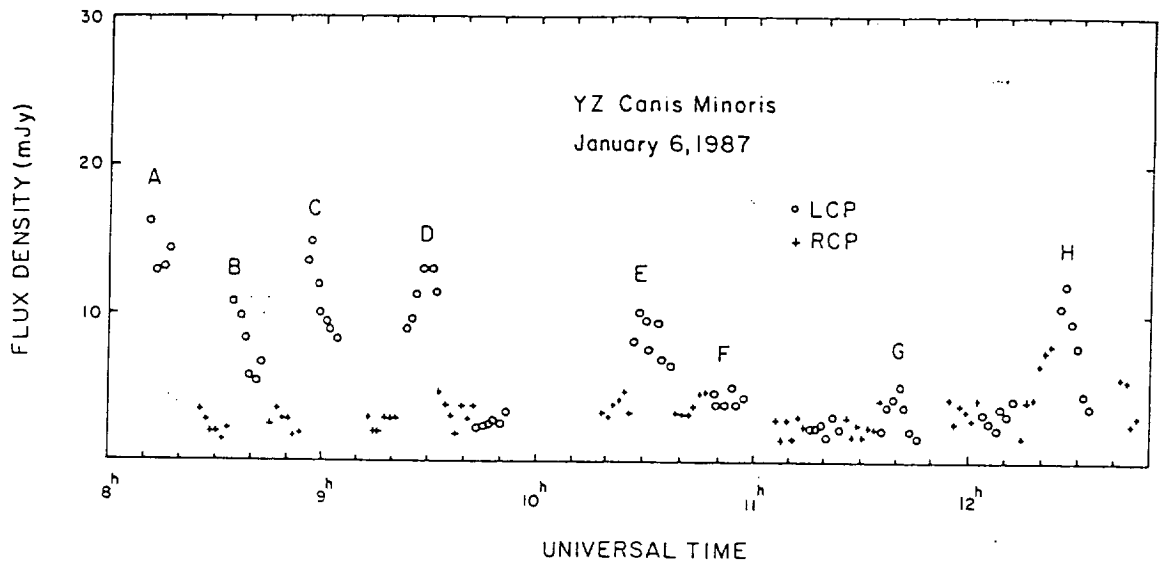


Figure 3. A five-hour VLA observation of the total intensity of the radiation from the dwarf M star YZ Canis Minoris in a 50 MHz bandwidth centered at 1464.9 MHz. The radiation is 100 percent left-hand circularly polarized. Its narrow-band frequency structure is illustrated in Fig. 4. (adapted from Lang and Willson (1986a)).

The long-duration, narrow-band highly polarized radiation (see Figures 3 and 4) is unlike any flares observed on the Sun, and cannot be easily explained using the solar analogy. The energy release mechanism lasts at least an order of magnitude longer than solar flares, and is difficult to understand if magnetic reconnection is the source of energy for the stellar flares (White, Kundu and Jackson, 1986). The narrow-band structure cannot be attributed to continuum emission processes such as thermal bremsstrahlung, thermal gyroresonant radiation, or nonthermal gyrosynchrotron radiation; it may be due to coherent mechanisms like electron-cyclotron masers or coherent plasma radiation. Both mechanisms require a magnetic field to produce the high circular polarization - either at the site of radiation production or during subsequent propagation of initially unpolarized radiation.

The coherent radiation processes provide constraints on the physical conditions in the coronae of flare stars (Lang, 1986). An upper limit to the electron density in the source is given by the requirement that the observing frequency must be greater than the

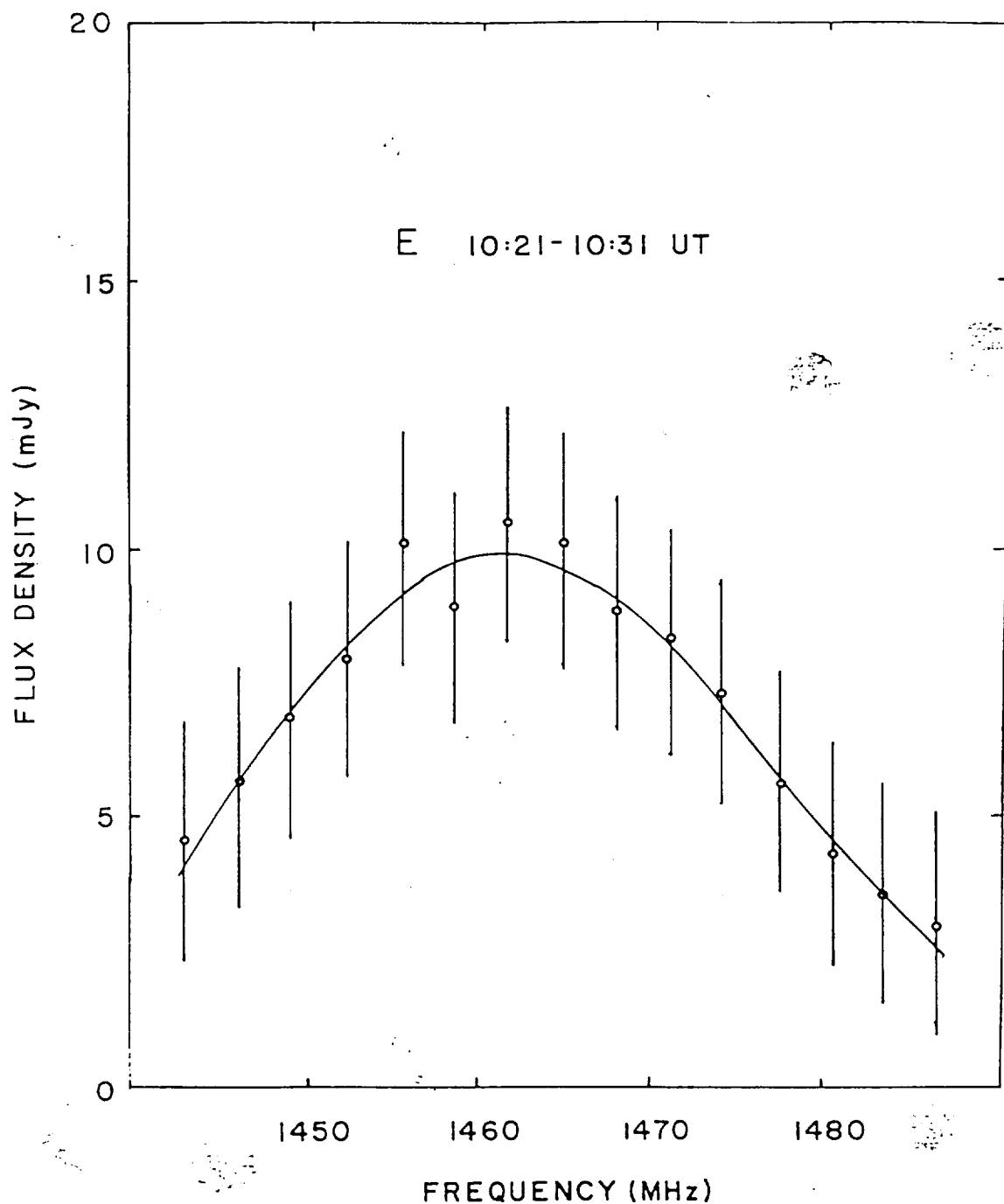


Figure 4. Frequency spectrum of the left circularly polarized radiation from YZ Canis Minoris for the interval marked E in Figure 1. Here the total intensity is plotted for 15 contiguous channels, each 3.125 MHz wide, for the 10-second interval. These data, as well as those for other intervals lettered in Fig. 3, show evidence for narrow-band radiation with a bandwidth  $\Delta\nu < 30$  MHz, or  $\Delta\nu/\nu = 0.02$ . (Adapted from Lang and Willson (1986a)).



plasma frequency for the radiation to propagate out and reach the observer; at 20-cm wavelength this requires  $N_e < 2.5 \times 10^{10} \text{ cm}^{-3}$ . If an electron-cyclotron maser emits at the second or third harmonic of the gyrofrequency, then a coronal magnetic field strength of  $H = 250 \text{ G}$  or  $167 \text{ G}$  is required to explain the 20 cm radiation. Coherent plasma radiation at the second harmonic of the plasma frequency requires an electron density of  $N_e = 6 \times 10^9 \text{ cm}^{-3}$ . If coherent plasma radiation dominates, then the plasma frequency must be larger than the electron gyrofrequency, thereby providing an upper limit to the magnetic field strength  $H < 250 \text{ G}$ .

#### 4. TEMPORAL STRUCTURE OF RADIO FLARES

##### 4.1 Rapid Variations

Radio flares from the dMe star AD Leonis near 20 cm wavelength consist of rapid ( $< 100$  milliseconds), highly-polarized (up to 100% left-hand circularly polarized) spikes whose rise times provide stringent limits to the size and brightness temperature of the radio source. Such rapid variations were first observed by Lang et al. (1983) using the Arecibo Observatory (see Figure 5). They have been confirmed by Bastian et al. (1990) using the same radio telescope, and by Gudel, et al. (1989) whose simultaneous observations with the radio telescopes in Effelsberg, Jodrell Bank and Arecibo substantiated the common origin of the radiation and eliminated any remaining doubts about its stellar origin (the time coincidence of flares observed at the three sites was within 0.4 seconds).

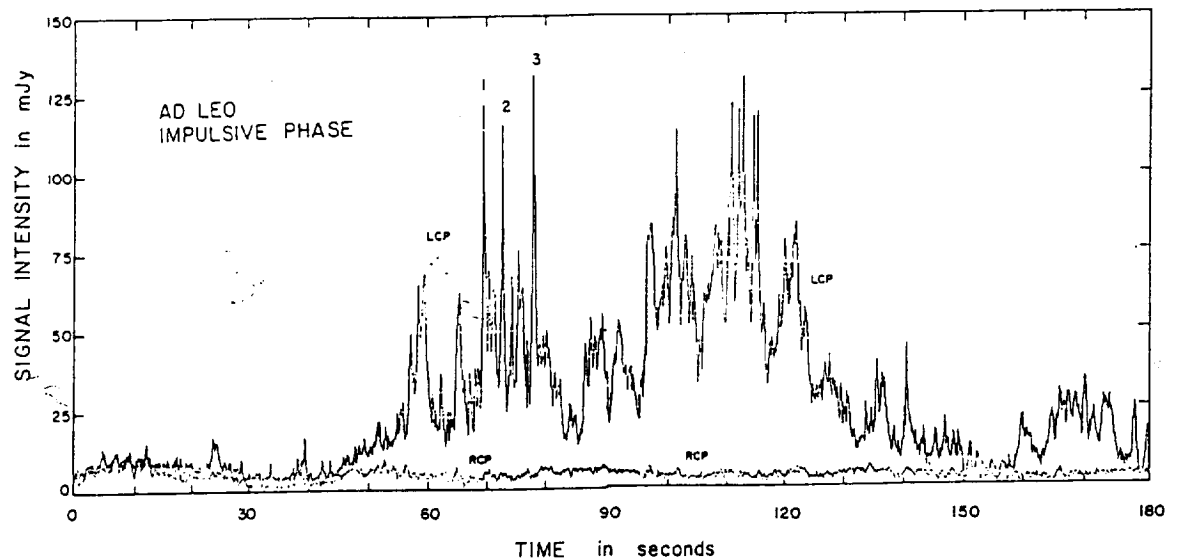


Figure 5. These observations, taken at 1400 MHz (21 cm) with the Arecibo Observatory, indicate that highly left-circularly polarized (LCP) radiation from the dwarf M star AD Leonis consists of rapid spikes whose duration  $\tau < 100$  milliseconds. The emitting source must be much smaller than the star in size. (Adapted from Lang et al. (1983)).

The spikes labeled 1,2 and 3 in Figure 5 have rise times  $\tau < 200$  milliseconds, and upper limits of  $\tau < 20$  milliseconds have been observed. An upper limit to the linear size,  $L$ , of the emitting region is provided by the distance that light travels in time,  $\tau$ , or  $L < c \times \tau$ . A light-travel time of 20 milliseconds indicates  $L < 6,000$  km, which is less than 1% of the stellar diameter. If the burst emitter is symmetric, it has an area less than 0.0003 of the stellar surface area, and the brightness temperature,  $T_B$ , is  $T_B > 10^{15}$  K.

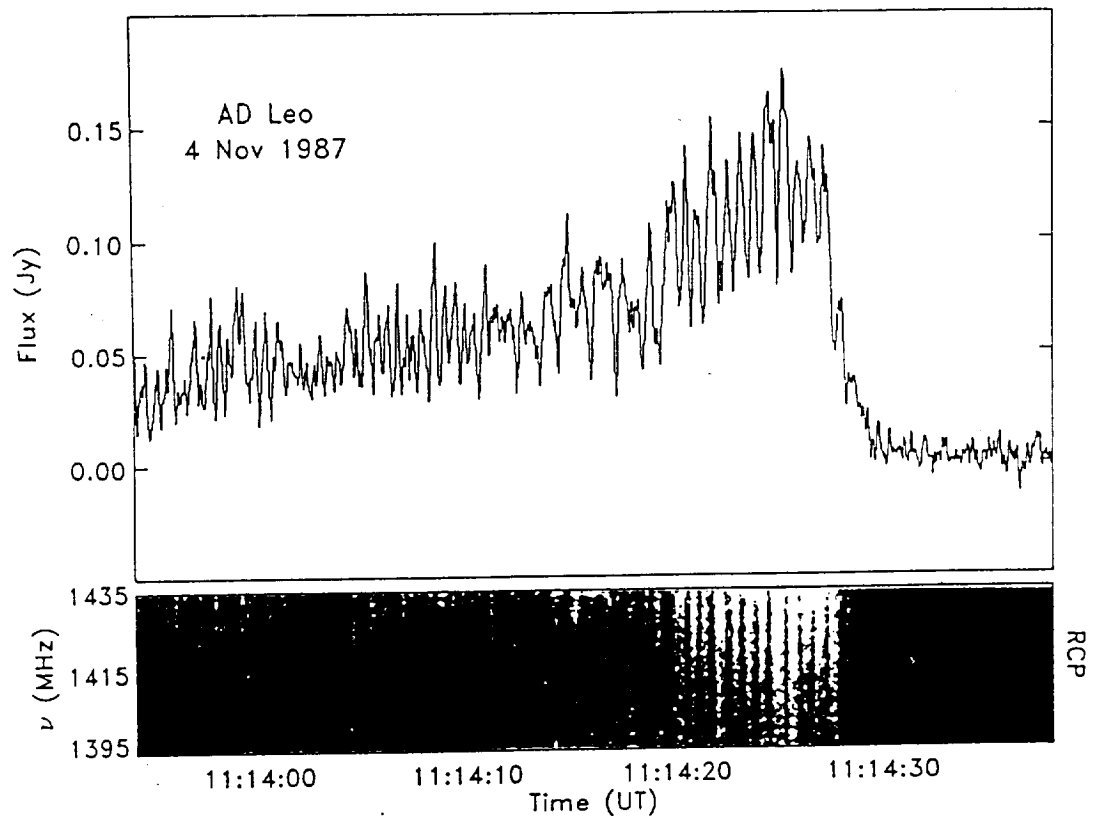


Figure 6. Observations of AD Leonis at 1415 MHz (21 cm) with the Arecibo Observatory indicate quasi-periodic pulsations with an amplitude modulation of  $\approx 50$  percent and a period of  $\approx 0.7$  seconds (top). The dynamic spectrum (bottom) indicates that the pulsations are broad-band with bandwidths  $\Delta\nu > 40$  MHz. (Adapted from Bastian et al. (1990)).

#### 4.2. Quasi-Periodic Fluctuations

Radio flare emission from AD Leonis has also been resolved into a multitude of broad-band, quasi-periodic fluctuations called pulsations. Such pulsations have been reported by Lang and Willson (1986), Gudel et al. (1989) and Bastian et al. (1990); and example is shown in Figure 6. The typical interval between pulses is about 1 second, which

is comparable to that of solar decimetric pulsations. The AD Leo pulsations are up to 100% circularly polarized; they are coherent across the observing bandwidths of up to 100 MHz. They might be attributed to oscillations in a coronal loop with dimensions of about 5,000 km, which is close to the upper size limit inferred from the light-travel time.

## 5. FREQUENCY STRUCTURE OF RADIO FLARES

Observations of the radio radiation intensity as a function of both time and frequency (dynamic spectra) can independently confirm the small size of the radio emitter and provide insights to the relevant plasma processes. Dynamic spectra of UV Ceti near 20 cm wavelength (Bastian and Bookbinder, 1987) indicated, for example, both broad-band ( $> 40$  MHz) and narrow-band ( $\Delta\nu/\nu < 0.002$ ) features. The narrow-band emission is most likely due to a coherent radiation mechanism. A spectral component with a width,  $\Delta\nu$ , of 0.2 percent of the central frequency,  $\nu$ , puts an upper limit on the source diameter of 200 km, assuming a scale height of one stellar radius, the largest reasonable. If an electron-cyclotron maser is responsible, the magnetic field strength  $H \approx 250$  G and the electron density  $N_e < 10^9 \text{ cm}^{-3}$ .

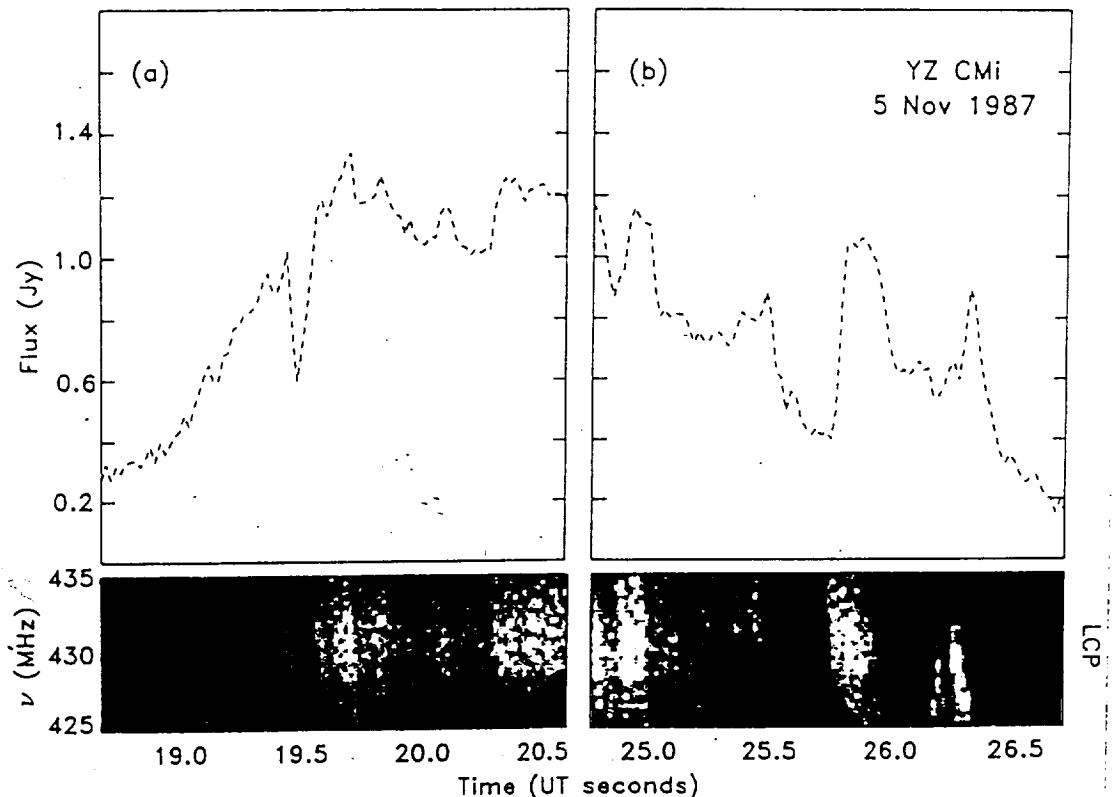


Figure 7. These Arecibo observations of the dynamic spectra (lower panel) of the 430 MHz (70 cm) radiation from the dwarf M star YZ Canis Minoris indicate a sudden reduction feature, in (a), with a drift in frequency of 250 MHz/s from high to low frequencies, as well as other narrowband and drifting features in (b). (Adapted from Bastian et al. (1990)).

Dynamic spectra of the radio radiation from the dMe flare stars AD Leo, YZ Cmi and UV Ceti show considerable complexity, with both narrow-band and broad-band features, and both positive and negative frequency drifts (Bastian and Bookbinder, 1987; Jackson, Kundu, and White, 1987; Bastian et al., 1990). The example shown in Figure 7 has a negative drift of 250 MHz per second from high to low frequencies. Such a negative drift is commonly observed in the Sun (eg. type II and type III bursts) suggesting electron beams or shock waves that propagate outwards in the stellar corona. But positive frequency drifts have also been observed for flare stars, suggesting a disturbance that propagates downward in the stellar corona and progressively excites plasma radiation at higher frequencies (larger electron densities).

Thus, there is clear evidence for apparent frequency drifts and narrow-band features in radio flares from dMe stars, but their interpretation is currently open to question. They could be due to the propagation of an exciter, group delays or some other cause.

## 6. DISCUSSION

To sum up, the quiescent radio radiation from dMe stars might be due to exceptionally hot thermal electrons, nonthermal electrons, or near continual coherent flaring. The high brightness temperatures, strong circular polarization and narrow frequency extent of long-duration radio events require a coherent plasma process, as does the more impulsive stellar radio flares. The cyclotron maser could explain many aspects of the flaring emission (Dulk, 1985), but several other coherent radiation processes might be involved (Kuijpers, 1989; Mullan, 1989). When the correct radiation mechanisms are identified, perhaps as the result of future observations with broader bandwidths, we can accurately specify the physical parameters in the stellar coronae.

Different processes probably dominate at different wavelengths, as they do on the Sun, and both solar and stellar flares must be related to magnetic fields. Past theoretical studies of solar radio radiation can therefore provide a useful background for exploring plausible radiation mechanisms. However, the direct analogy of the Sun as a radio flare star is probably a mistake; the Sun is the wrong spectral type, and its radio flares are so weak that they would be undetectable at the distance of the nearest star. In addition, solar flares have near-simultaneous signatures at optical, radio and X-ray wavelengths, while flaring radio emission from the dMe stars is often undetectable in other regions of the electromagnetic spectrum (see for instance Kundu et al. (1989)). The available evidence therefore indicates that radio flares from dwarf M flare stars are physically very different from those occurring on the Sun.

## 7. ACKNOWLEDGMENTS

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